

PROPAGATION MODELS USED IN THE STUDIES OF UWB/GPS INTERFERENCE

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Introduction: This document is a summary of what may be learned about the models for radiowave propagation that have been used in connection with recent assessments of the impact of ultrawideband (UWB) devices in the vicinity of Global Positioning System (GPS) receivers. The reading of the reports of these assessments has been undertaken in order to determine what, if any, contribution that the Advanced Networking Technologies Division (ANTD) can make to the Networking in the Extreme (NETEX) project of the Defense Advanced Research Projects Agency (DARPA), and it is felt that the interference question is a possible area for ANTD work in support of the project.

The particular interest in the propagation model aspect of these studies has arisen in part because of comments by several DARPA presenters at the NETEX project's Industry Day on September 10, 2001:

- Dr. Mari Maeda, program manager for the NETEX project, said [1] that one of the objectives of Phase 1 of the project is to "sort out myth from reality," referring to the fact that there have been many claims made that UWB radio systems have special properties, such as immunity to multipath fading.

- Dr. James Freebersyser, another DARPA program manager, said [2] that some of the basic questions relating to the performance and application of UWB devices to communication systems have yet to be answered quantitatively, including a detailed link budget, and went so far as to say that "UWB propagation models do not exist" and "narrowband assumptions in link budget calculations are violated" by UWB systems.

- Dr. R. A. Scholtz of the UltRa Lab at USC, commented [3], as one of a team of "enthusiastic skeptics" actively studying UWB systems, that the question of whether the propagation of UWB signals is adequately described by current propagation models is a complex question ("the devil is in the details"). Most UWB propagation studies to date (e.g., [4]-[5]) are concerned with multipath profiles. On one of his webpages [6] Dr. Scholtz says in reference to an UWB testing setup, "Since the antenna system differentiates and filters the pulser's output, a more complex waveform is detected by the [receiver]"; the waveform shape itself is affected by the antenna for an UWB signal, much more so that for a narrowband signal.

In what follows, the methodologies found in the principal documents relating to the assessment of UWB/GPS interference are summarized in terms of their assumptions regarding the propagation of the interfering UWB signals.

1. D. S. Anderson *et al.*, "Assessment of Compatibility Between Ultrawideband (UWB) Systems and Global Positioning System (GPS) Receivers," NTIA Special Publication 01-45, February 2001.

In this study, a propagation model is used to extrapolate laboratory results to certain scenarios in which an UWB device may interfere with a GPS system when the UWB device is operating at the signal levels permitted by FCC Part 15 regulations for unlicensed emitters. The laboratory results indicate the UWB signal threshold levels at the GPS receiver that cause the GPS system to malfunction, different threshold levels for different types of UWB waveforms. When the calculations of in-band UWB power for a particular scenario and UWB waveform type result in a signal level that exceeds the threshold level by X dB, the assessment is that effective isotropic radiated power (EIRP) of the UWB transmitter must be reduced by X dB in that case. For example, the EIRP of an UWB transmission of pulses at an average pulse repetition frequency (PRF) of 20 MHz must be reduced in power by 41.6 dB relative to the Part 15 levels for a particular scenario, 33.3 dB if the pulse positions are dithered [7].

The assumption in this methodology can be described as follows: Let the one-sided spectrum of the UWB signal at the transmitter be denoted $S(f)$. The effective isotropic radiated power (EIRP) is the integral of the spectral power density at the antenna:

$$\text{EIRP} = \int_0^{\infty} df S(f) \approx \Delta f \sum_k S(f_k) \quad (1.1)$$

for some Δf . At the receiver, the power from the UWB source is affected by the propagation loss, which is a function of frequency, among other parameters. If the channel is adequately modeled by a linear filter, the effective spectrum of the total UWB signal at the receiver location is $S(f)L(f; d)$, where d is the link distance. Suppose that Δf is the bandwidth of the GPS receiver, and that the received power in the bandwidth of the receiver from the UWB signal is $P_i = S(f_i)L(f_i; d)$. As long as the power in the GPS bandwidth at the receiver is linearly related to the transmitter EIRP, if the received power must be reduced to αP_i in order to meet non-interference requirements, then it is sufficient (though not logically necessary) to reduce the EIRP from the transmitter to αEIRP , as recommended in the report. Any alternative procedure that reduces the in-band interference would work.

In the scenario link budgets discussed in Section 3.1.3 (pp. 3-2 and 3-3), the propagation loss model "for the frequency range of interest" is the free space model for distances less than a "breakpoint radius" and a fourth-power-law model for greater distances. The breakpoint radius in units of miles is given in this report as $2.3 \times 10^{-7} h_t h_r f_{\text{MHz}}$, where h_t and h_r are the transmitter antenna height and receiver antenna height, respectively, given in units of feet and f_{MHz} is the center frequency given in MHz. Therefore, the model used is free space for the shorter distances and the two-ray, flat-earth multipath model for greater distances (see Appendix A.1, below). Evidently, it is assumed in the report that the propagation loss for the portion of the UWB signal's spectrum that falls within the relatively narrow GPS bandwidth can be estimated by the loss incurred by a narrowband signal placed at the center frequency of the GPS bandwidth. It will be of interest to see if the other reports treat ultrawideband signal propagation loss differently.

For all of the scenarios cited in the report, the distance between the UWB device and the GPS receiver is less than the breakpoint radius, so that free-space propagation is assumed to apply.

2. M. Cardoza, D. Cummings, and A. Kerkhoff, "Final Report: Data Collection Campaign for Measuring UWB/GPS Compatibility Effects," Applied Research Laboratory report TL-SG-01-01, University of Texas at Austin, 26 February 2001.

This report by the Applied Research Laboratory of the University of Texas (UT:ARL) summarizes measurements taken under contract to The Ultra Wideband Testing Consortium through Time Domain Corporation in Huntsville, AL. The measurements, which involved both conducted and radiated interference to a GPS receiver by a UWB devices, do not correspond to particular UWB/GPS scenarios but can be extrapolated to those scenarios.

In particular, as the report states, the conducted measurements do not include the effects of the channel and the antennas, which must be added in applying the measurement data to a particular scenario. The link budget equations suggested for such application assume that free-space propagation is the appropriate model to use and that the propagation loss experienced by a portion of the UWB device's spectrum can be used to scale the EIRP of the device.

The notation and discussions are somewhat unconventional in the use of terminology. For example, in describing the types of UWB signals generated, the term "duty cycle" was used to denote the fraction of time the carrierless pulse-modulated UWB signal is gated ON; evidently this same terminology is used by the manufacturer of the UWB signal generators used in the measurements. (This same identification of duty cycle with gating, regardless of the type of waveform, is used in other reports as well.)

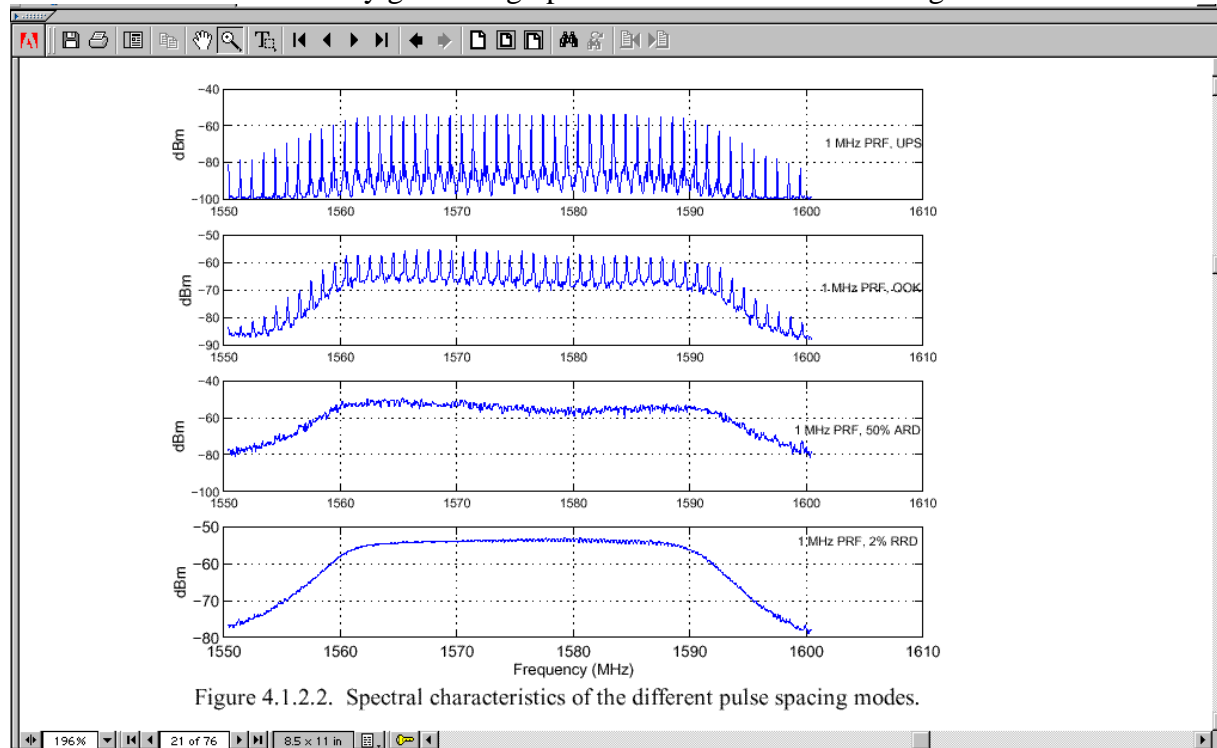
3. J. R. Hoffman, et al., "Measurements to Determine Potential Interference to GPS Receivers from Ultrawideband Transmission Systems," NTIA Report 01-384, February 2001.

NOTE: This report is a companion to NTIA Report 01-383 [2], which characterizes UWB signals in the time and frequency domains.

This report (NTIA 01-384) describes laboratory measurements of UWB signal levels that cause degradation of performance and malfunctioning in GPS receivers. Significantly, it says, "Conventional methods of measuring and quantifying interference under narrowband assumptions are insufficient for testing UWB interference" (p. 1-1), referring to the variable in-band characteristics of an UWB depending on its specific parameters, as opposed to those of noise or noiseliike interference. In fact, the amplitude probability distribution (APD) is non-Gaussian, in general (e.g., p. 5-2 and p. 6-2).

The tests described in the report are conducted (non-radiating) tests using a pulse generator and triggering source to develop various UWB signal types by varying pulse repetition frequency (PRF), dither, and gated duty cycle. Unmodulated pulse trains produced in-band interference with peaks spaced at the PRF, while dithered, low gated duty cycle pulse trains

produced noiselike in-band interference (p. 4-7, see Figure 4.1.2.2, below). Aggregate UWB interference was simulated by generating up to six simultaneous UWB signals.

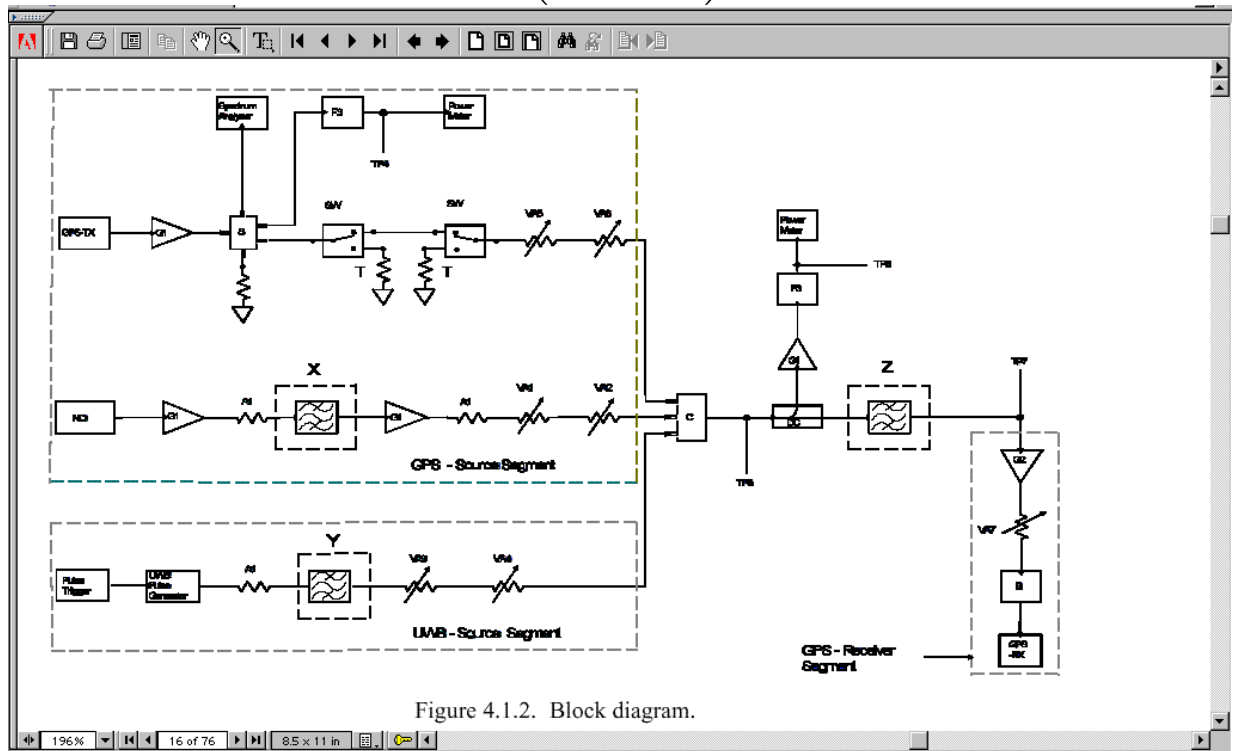


It is stated that negligible differences (in terms of time and frequency characteristics) were found between conducted UWB signals delivered to the antenna port of the GPS receiver from radiated UWB signals delivered to the same point in an anechoic chamber through the GPS antenna. This statement is hard to believe, considering the potential filtering effect of the antenna. However, the diagram of the conducted test setup (Figure 4.1.2.1, shown below) has a bandpass filter in the path of the UWB signal that simulates the filtering effect of the antenna.

The report presents a rather thorough statistical characterization of the performance of the GPS receiver with and without the UWB interference.

NTIA 01-384 does not consider propagation models because it is about laboratory tests. However, the companion report, NTIA 01-383 [8], does consider propagation in Section 4 in the course of developing the received power from an aggregation of UWB transmitters that are distributed randomly in distance from the receiver. The Irregular Terrain Model (ITM) of the Institute for Telecommunication Sciences (ITS), also known as the Longley-Rice propagation model [9, 10, 11], is used in the area prediction mode to estimate the average path loss for a particular transmitter location, which is averaged over the distances of the UWB transmitters. The assumption being made is that the aggregate UWB power at the receiver can be modeled as the superposition of UWB powers at various locations and that the effect of the medium on a UWB transmitter's power is attenuation according to the semi-empirical model implemented as the ITM. To account for the very short distances that are common to UWB interference scenarios, the free-space propagation component of the attenuation is reformulated in a way that can be expressed by

$$L_{fs}(\text{dB}) = 20 \log_{10} \left(\frac{4\pi d}{\lambda} + 1.64 \right) \quad (3.1)$$



which closely approximates near-field measured results as the distance d becomes small. The methodology in this calculation does not take the bandwidth of the transmitter's signal as a parameter, so that UWB signals are treated no differently than narrowband signals with the same center frequency.

Some comparisons of UWB conducted and radiated spectrums are given, showing significant differences in some cases, unlike the results stated in NTIA 01-384. The harmonization of these conflicting results may be that the test setup in NTIA 01-384 considers only the portion of the spectrum in the GPS receiver band, while that in NTIA 01-383 considers the whole spectrum. While radiated measurements were taken, they were taken at the short distance of one meter, and no effort to characterize the propagation characteristics of the UWB signals is described in these reports.

4. Anon., "Final Report UWB-GPS Compatibility Analysis Project," Johns Hopkins University/ Applied Physics Laboratory, 8 March 2001.

The JHU/APL report describes their assessment of the effects of UWB emissions on GPS receiver performance, based on a statistical evaluation of the data collected by UT:ARL "along with a strictly theoretical analysis." Therefore the report states simply that Part 15-compliant UWB devices that are less than three meters from a GPS receiver severely degrades the performance of the receiver. At greater distances, the performance is more or less acceptable, depending upon the particular combination of UWB device and GPS receiver model. The significance of

the three-meter distance is that the FCC Part 15 emission limit for frequencies about 960 MHz is stated in terms of a 500 microvolt/m field strength at a distance of three meters from the radiator, in addition to certain limits on peak signal strength. The radiated interference tests at UT:ARL were used in the analysis of JHU/APL to calibrate an extrapolation of the UT:ARL conducted interference tests to various distances between the UWB devices and the GPS receiver.

This report is outstanding in its presentation quality, and serves as a comprehensive reference for the whole subject. Mathematical models are given for UWB "pulselets" and their spectra. The UT:ARL test data are neatly summarized in a table (page 4-14).

In extrapolating conducted interference measurement data, the attenuation settings for the UWB signal are converted to an equivalent standoff distance by assuming $1/R^2$ field strength geometric dilution and a frequency-dependent receiving antenna transfer function—essentially free-space propagation.

A clear theoretical analysis is given of the effect of pulse train modulation on the spectrum of the UWB signal and the resultant spectrum in the bandwidth of the GPS receiver is calculated and its effect on the GPS correlator is determined for comparison with measurements. It is noted that a nonlinearity in the transmission path affects individual pulses (pulselets) separately, so that the output of the nonlinearity is still represented as the convolution of a single (modified) pulse waveform and a train of impulses.

APPENDIX

A.1 Two-ray propagation model. As described in [1, §2.1.3.1] and elsewhere, the propagation loss for the two-ray model is given by

$$\frac{P_r}{P_t} = \left(\frac{\lambda}{4\pi d} \right)^2 \times 4 \sin^2 \left(\frac{2\pi h_t h_r}{\lambda d} \right) \quad (\text{A1.1})$$

where P_r is the received power, P_t is the transmitted power, λ is the wavelength of the center frequency of the waveform, and d is the radial distance, with all like quantities expressed in the same measurement units. The angle of the sine function is less than $\pi/6$ where the distance is greater than d' , where

$$d' = \frac{12 h_t h_r}{\lambda} \quad (\text{A1.2a})$$

When this distance is expressed in meters, for example, it has the formula

$$d'(\text{m}) = \frac{12 h_t(\text{m}) h_r(\text{m})}{\lambda(\text{m})} = \frac{12 h_t(\text{m}) h_r(\text{m})}{299.8/f_{\text{MHz}}} = 4.003 \times 10^{-2} h_t(\text{m}) h_r(\text{m}) f_{\text{MHz}} \quad (\text{A1.2b})$$

When this distance is expressed in miles with antenna heights in feet, it has the formula

$$d'(\text{mi}) = \frac{d'(\text{ft})}{5280} = \frac{12 h_t(\text{ft}) h_r(\text{ft})}{5280 \lambda(\text{ft})} = \frac{12 h_t(\text{ft}) h_r(\text{ft})}{5280 \lambda(\text{m})/0.3048}$$

$$= \frac{0.3048 \times 12 h_t(\text{ft}) h_r(\text{ft})}{5280 (299.8/f_{MHz})} = 2.31 \times 10^{-6} h_t(\text{ft}) h_r(\text{ft}) f_{MHz} \quad (\text{A1.2b})$$

Therefore the breakpoint distance quoted in NTIA 01-45 is the quantity given by (A1.2a). Further, for small distances, NTIA 01-45 assumes no significant close-in multipath, resulting in the line of sight (LOS) model obtained by ignoring the sinusoidal factor in (A1.1) to get the free-space propagation model for loss, given in dB by

$$L_p = 10 \log_{10} \left[\left(\frac{\lambda}{4\pi d} \right)^{-2} \right] = 20 \log_{10}(4\pi) + 20 \log_{10}(d) - 20 \log_{10}(\lambda) \quad (\text{A1.3a})$$

where the values of d and λ are given in the same measurement units. For example, for d and λ both in units of meters, the free-space propagation loss has the formula

$$\begin{aligned} L_p &= 10 \log_{10} \left[\left(\frac{\lambda(\text{m})}{4\pi d(\text{m})} \right)^{-2} \right] = 10 \log_{10} \left[\left(\frac{299.8}{4\pi f_{MHz} d(\text{m})} \right)^{-2} \right] \\ &= 20 \log_{10} \left(\frac{4\pi}{299.8} \right) + 20 \log_{10}(d(\text{m})) + 20 \log_{10}(f_{MHz}) \\ &= 20 \log_{10}(d(\text{m})) + 20 \log_{10}(f_{MHz}) - 27.55 \end{aligned} \quad (\text{A1.3b})$$

For d in kilometers, the formula becomes

$$\begin{aligned} L_p &= 20 \log_{10}(1000 d(\text{km})) + 20 \log_{10}(f_{MHz}) - 27.55 \\ &= 20 \log_{10}(d(\text{km})) + 20 \log_{10}(f_{MHz}) + 32.45 \end{aligned} \quad (\text{A1.3c})$$

For d in miles, the formula becomes

$$\begin{aligned} L_p &= 20 \log_{10}(0.3048 \times 5280 d(\text{mi})) + 20 \log_{10}(f_{MHz}) - 27.55 \\ &= 20 \log_{10}(d(\text{mi})) + 20 \log_{10}(f_{MHz}) + 36.58 \end{aligned} \quad (\text{A1.3d})$$

For distances larger than the breakpoint radius d' , the formula in (A1.1) becomes

$$\frac{P_r}{P_t} \approx \left(\frac{\lambda}{4\pi d} \right)^2 \times 4 \left(\frac{2\pi h_t h_r}{\lambda d} \right)^2 = \left(\frac{h_t h_r}{d^2} \right)^2 = \frac{(h_t h_r)^2}{d^4} \quad (\text{A1.4})$$

which is the well known "fourth power law" propagation loss formula. Note that frequency is not a variable in this formula. In most outdoor physical situations, the magnitude of the interfering path is less than that of the direct path, so that the actual propagation loss increase as a function of distance is between 3 and 4, depending on the antenna height.

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